AEMT

Association of Electrical and Mechanical Trades

GOOD PRACTICE GUIDE

THE REPAIR OF INDUCTION MOTORS

Best Practices to Maintain Energy Efficiency

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DEPARTMENT OF THE
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BEST PRACTICE PROGRAMME
ENERGY EFFICIENCY

Association of Electrical and Mechanical Trades

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THE REPAIR OF INDUCTION MOTORS

Best Practices to Maintain Energy Efficiency

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IMPORTANT NOTICE

This Good Practice Guide has been prepared for use in the Electrical Repair Industry.

Other Energy Efficiency Best Practice Programme publications can be obtained from the Energy Effiency Bureau, ETSU, Harwell, Oxfordshire, OX11 ORA. Tel No. 01235 436747. Fax No. 01235 432923. E-mail etsuenq@aeat.co.uk.

CONTENTS

LIST OF DIAGRAMS

INTRODUCTION

This Good Practice Guide covers the repair of small/medium sized induction motors for operation on low-voltage, three-phase supplies, and whose stators are "random" or "mush" wound, as distinct from geometrically formed coils as used in larger machines.

It has been estimated that reductions in the efficiencies of such motors as a result of being repaired without due attention to retaining energy-efficient characteristics, could cause a cumulative loss in electrical energy throughout the U.K. of about 240 GWh per annum, costing more than £10m.

Traditionally, the principal aims of the electric motor repair shop have been:

- reliability of the repaired product;
- speedy service, to minimise down-time in the customer's plant.

There has been only minimum awareness by some repairers of the degree to which losses could be increased by certain practices, and generally none by customers, that a repaired motor could be less efficient than when new.

This lack of awareness is not surprising, when it is recalled that it was only in the 1980s that improved levels of energy efficiency of new motors became commercially available from the manufacturers, and that the initial response in the market place was muted.

Electric Motor Manufacture Since 1980

Before returning to the subject of motor repairs, it is relevant to look at the motor manufacturing industry, and the product developments leading to the present "state of the art."

Historically, three-phase induction motors, although inherently efficient converters of energy, had been designed commercially to minimise materials and cost, subject to meeting established performance standards. Then in 1982 a major U.K. manufacturer became the first in Europe to develop and market an "Energy Efficient" full line of motors.

Thus, a new range of machines, offered alongside the existing standard range, presented the purchaser for the first time with the option of mechanically interchangeable motors of typically 3% increased energy efficiencies. These motors, albeit more costly to produce and therefore carrying a price premium, could enable the user to make savings in electricity bills, which would recover their higher initial cost within cost-effective payback periods, typically two years or less.

In the period during which the "Energy Efficient" motors have been available, they have steadily increased in popularity amongst the more discriminating users. However, the majority of electric motors were purchased not by the ultimate users, but by the original equipment manufacturers, who obviously did not find the more expensive motor more attractive. It therefore remained a minority product in terms of volume production.

State of the Art: U.K.

With the above background, the principal U.K. electric motor manufacturer has taken another new ititiative, whereby after an extensive collaborative development involving the manufacturer of magnetic steel, and with a new design strategy, their "Higher Efficiency" motors are now being introduced as their new standard range. With only marginal increases in active materials over the existing standard range, the new motors give energy savings approaching those of the “Energy Efficient” machines, but without the penalty of a price premium.

It has been estimated that as existing electric motors in the U.K. are gradually phased out, and replaced in the future by this new generation of motors, the total saving in electricity consumption will be in the order of £120m p.a.

Quite apart from the financial benefits to individual motor users, it is obvious that this important development is in the national interest, and this has been recognised by H.M. Government, who have contributed to the development costs through grants by the Department of Environment, under the Energy Efficiency Best Practice Programme.

State of the Art: North America

Before leaving the subject of energy efficiency of new motors it is of interest to consider the trends in other countries, but particularly in North America, where the efforts to improve standards of energy efficiency of new electric motors have been promoted more aggressively by all the parties concerned than elsewhere in the world. In this, the U.S.A. and Canada have acted more-or-less in concert, with Canada generally being ahead of the U.S.A. in implementation.

The various stages of development have been as follows:

- a mandatory requirement for manufacturers to mark motor efficiencies on the rating plates, to claim compliance with NEMA and CSA standards;
- publication by NEMA and CSA of tables of specified minimum values of full-load efficiencies of (a) standard motors and (b) Energy Efficient motors;
- financial incentives, paid by the Utilities, with Government support, to encourage the purchase and installation of Energy Efficient motors;
- legislation, making it a statutory requirement that all new motors must comply with the specified Energy Efficient performance figures. Regulatory bodies will verify the measurements of energy efficiencies. The new legislation became effective in Canada in January 1996, to be followed in the U.S.A. in October 1997.

The Repair of Electric Motors

The foregoing paragraphs have shown that a trend towards higher energy efficiencies, which in its beginnings ten years ago affected a minority of new motors installed, is now reaching a stage where all new motors will have enhanced efficiencies compared with the previous generation of standard motor designs. It is the responsibility of the electrical machinery repair industry, particularly through its trade association AEMT, to ensure that the savings in electricity consumption resulting from the initiatives of the manufacturers are not offset by losses resulting from avoidable practices in repair shops. This is the objective of this Best Practice Guide.

In the compilation of the Guide, the results of a specially commissioned research project, investigating the effect of burn-out oven temperatures on motor core losses has been taken into account, also a study into the effects of winding specification changes typically practiced in repair shops.

Repair of Motors Used in Flammable Atmospheres

In the paramount interests of safety, applications in zones where explosive atmospheres may be present, require motors which not only comply with British or International Standards covering the various EX categories of motors, but which are also certified as such by BASEEFA or other recognised certifying authority.

This Good Practice Guide recommends many practices which, by preventing increased losses, would be beneficial in the repair of EX types. On the other hand, a few of the recommendations in this Guide, for example in the section entitled “Specifying the Replacement Winding,” could be construed as deviations from the motor design, and as such might infringe Certification.

Established practices in the repair industry, ensuring that EX Certificates are not invalidated, are covered in an AEMT Code of Practice entitled “REPAIR AND OVERHAUL OF ELECTRICAL EQUIPMENT FOR USE IN POTENTIALLY HAZARDOUS ATMOSPHERES,” and wherever they conflict with this Good Practice Guide, must be given precedence when repairing EX types.

ENERGY LOSSES IN INDUCTION MOTORS

The Losses Itemized

The energy losses can be grouped into two categories, shown in Table A, namely:

- constant (or "fixed") losses, which are virtually independent of the applied load and are itemized 1, 2 and 3 in the table;
- variable (load-dependent) losses, itemized 4, 5 and 6 in the table.

Table A. Itemized Loss Components and Their Causes

	Loss Component	Root Causes of Energy Loss
1.	Core losses (a) hysteresis (b) eddy current loss	(a) Energy expended by reversals of magnetic fluxes. (b) I^2R losses in core steel, caused by circulating currents induced by the flux reversals.
2.	Friction (a) bearings (b) seals (if any) (c) core rubs, etc.	(a) Rolling of the elements; viscous flow of the lubrication (b) Sliding of the elements; viscous flow of the lubrication (c) Not applicable to a well constructed, undamaged motor
3.	Windage (a) fan (b) rotor	(a) External cooling air friction and turbulence. (b) Internal air friction and turbulence, particularly due to rotor fins.
4.	Stator copper loss	I^2R, minimal at no-load, increases as load is applied. Increases additionally as the temperature increases.
5.	Rotor	I^2R in bars and end-rings, virtually zero at no-load, increases as the square of the load, and additionally as the temperature increases. Rotor core losses due to main flux are virtually zero.
6.	"Stray" losses	Additional load losses in stator and rotor, mainly caused by leakage fluxes and high frequency pulsations.

Fig. 1 illustrates how these itemized losses vary in relation to the applied load, in a typical 7.5 kW motor.

Any or all of the above loss components can be affected by alterations made to the motor during a repair. Table B gives examples (but not an exhaustive list) of how the losses can be adversely affected by such alterations. The following paragraphs explain in more detail how some of the factors listed in the right hand column of Table B specifically affect the individual loss components.

Core Loss Increases: Physical Influences

The only physical cause of increased hysteresis loss in core steel is mechanical stress. For example, if the stator frame has to be replaced, and the bore diameter is undersized, the increased interference fit between the frame and the stator core would subject the stator "back-iron" to excessive compressive stress. This would increase hysteresis loss.

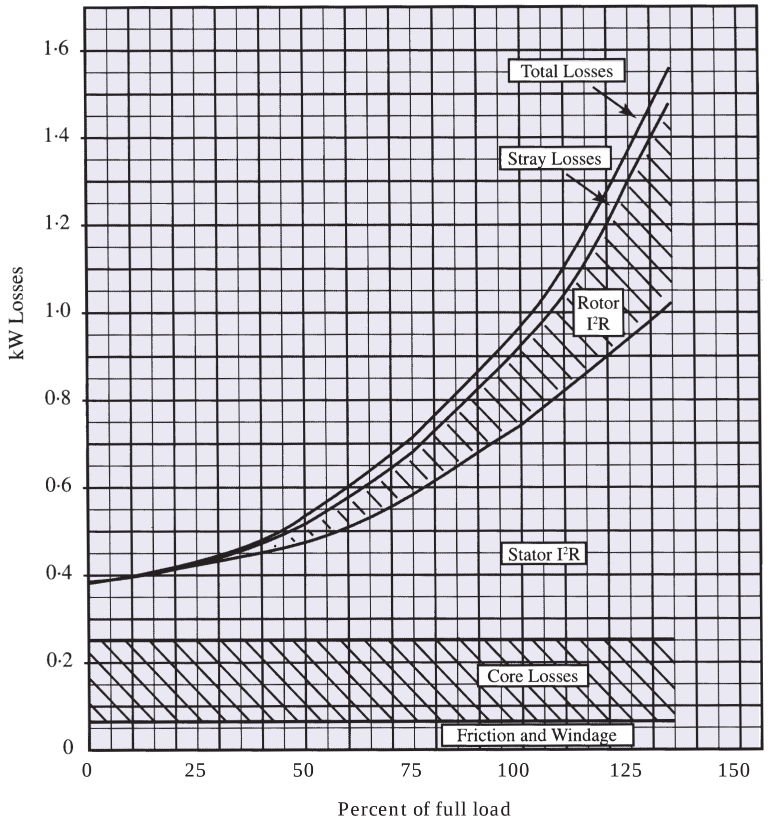


Fig. 1 Graph; component losses plotted against load

Table B. Examples of Modifications Which Would Cause Increased Losses

Loss Component		Modifications which would increase losses
1.	Core losses (a) hysteresis (b) eddy current loss	(a) Only: excessive mechanical stress in stator core, resulting from physical abuse or excessive interference fit when replacing or repairing a damaged frame. (b) Only: breakdown of inter-lamination insulation, resulting from damage; e.g., during burn-out. (a) and (b): increased magnetic fluxes, resulting from a changed winding specification.
2.	Friction (a) bearings (b) seals (if any) (c) core rubs, etc.	(a) Badly fitted bearing: excessive interference fits. (b) Badly fitted or incorrect seal: lack of lubrication. (c) Damaged parts or inaccurately machined replacements.
3.	Windage	Incorrect replacement fan with oversize blades.
4.	Stator copper loss	Changed winding specification; e.g., reduced conductor size, increased "length of mean turn" (LMT), changed number of turns, or changed configuration; increased air gap caused by machining stator bore or rotor.
5.	Rotor	Reduced magnetic flux, resulting from a changed winding specification; reduced end-ring section or broken bars.
6.	"Stray" losses	Changed winding specification; wrong replacement rotor; reduced air gap; air gap eccentricity.

There are other ways in which stresses can be set up in core steel. It is common practice to repair bent stator teeth (caused for example when stripping the windings) by physically hammering them back into position. This leaves residual stresses which increase local hysteresis. (As a point of interest, one of the reasons why some motor manufacturers anneal laminations after punching is to relieve residual stresses, which would otherwise increase hysteresis loss).

The eddy current loss component is caused by the induced currents within the laminated stator core. The laminations have insulating coatings which (provided they remain intact) minimise the eddy currents by containing them within the individual laminations. These coatings are in the form of either ferrous oxide film or synthetic varnishes. Any damage or degrading of the coatings could provide paths for the eddy currents to flow between adjacent laminations, thus increasing their magnitude.

The practice of heating stators to facilitate stripping the coils before rewinding can cause degrading, unless the process is adequately controlled. This has been investigated in a research project conducted specifically to assist the preparation of this Guide. This is described in Appendix2.

Damage to the coatings can of course be caused by the earth fault or short circuit which caused the motor to fail, if such fault occurs inside a slot or near an end lamination.

Other possible causes of increased eddy currents include bridging between the edges of laminations, resulting from core-rubs and/or over-rigorous use of power grinders, files, etc., for removing varnish or other deposits from the stator bore or slots.

Core Loss Increases: Electro-Magnetic Influences

There are two ways in which the core losses can be electro-magnetically affected, namely variations in the electrical supply, and changes to the winding (for example during a rewind).

Either of these changes will alter the magnetic flux and hence the magnetic flux densities in the various parts of the magnetic circuits, particularly in the stator “back-iron” and the teeth, and it is these that would in consequence affect the core losses.

Incidentally, any change in the magnetic flux would cause changes also in the flux densities in the rotor, but the flux reversals in the rotor are at a very low frequency, typically less than 2 Hz at full-load, and almost zero at no-load. Core losses in the rotor are therefore minimal, for mains-operated motors.

A more detailed account of the causes and effects of magnetic flux changes and particularly the effect on losses is given in Appendix 1.

THE MOTOR REPAIR PROCESS

The sections which follow are a breakdown of the total process of the repair of electric motors, into a logical sequence of operations, commencing with the receiving of the faulty machine, and culminating in the final testing of the repaired motor.

Only those aspects of the operations which fall within the remit of this Guide are discussed, namely those related to the efficiency of the product. In that context, methods which are considered to represent Good Practices are so indicated; conversely, practices which could be detrimental in terms of energy losses and motor efficiency are highlighted.

It is recognised that there are many other important requirements in the repair process, particularly in the area of Quality and Reliability, but these are outside the scope of this Good Practice Guide.

PRELIMINARY INSPECTION

The first stage of a motor repair includes an inspection of the damaged motor, a diagnosis of its condition and the cause of the problem. A judgement then has to be made regarding the feasibility of a repair, depending on the motor's condition.

Obviously there are cases where the motor has to be judged as beyond repair, if replacements for irreparably damaged parts are unavailable. In less extreme cases the repair cost may seem prohibitive, but the customer may nevertheless accept it to minimise down-time of his plant, to avoid the unacceptable delay of a new replacement.

Historically, the main consideration has been restoring the motor to a reliable operating condition. Within the scope of this Guide however, the repairer should also take into account an assessment of whether the damage is such, that the motor after repair would be sub-standard in terms of its energy efficiency.

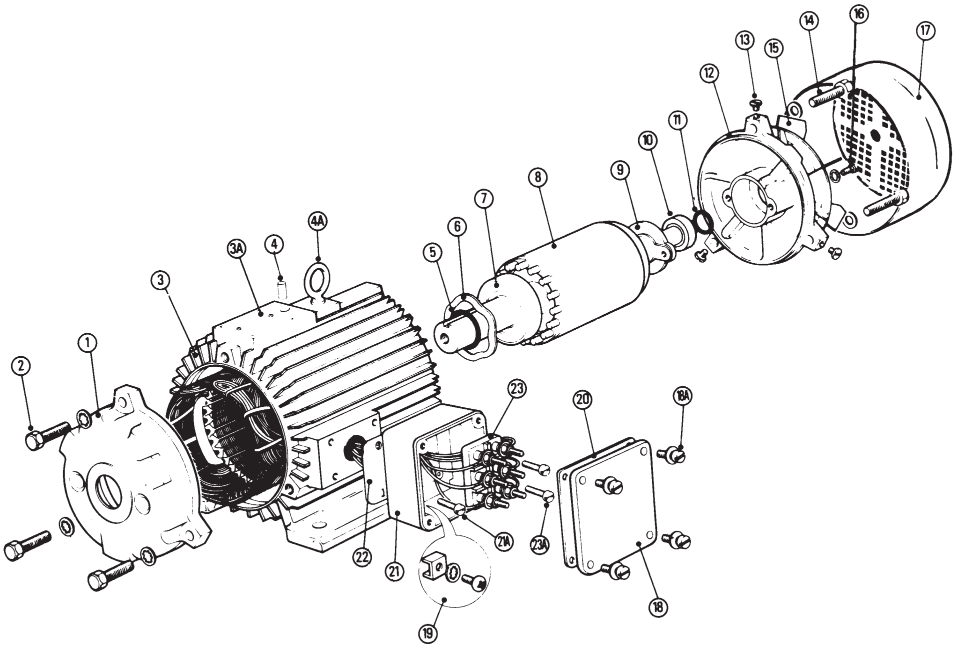
Irreversible Damage

Damage to the stator core during a previous repair may have been caused by the application of excessive heat prior to coil-pulling. Other causes of stator core damage could include coil blow-out inside a slot, or severe rubbing by the rotor after the collapse of a ball-bearing. Such damage would be likely to increase the core loss, so that after rewinding, although the motor might appear to operate satisfactorily, there would be a reduction in its efficiency, ongoing energy cost increase to the customer, and incidentally, increased temperature rise with reduced life expectancy.

It would be good practice in such cases to convey this assessment to the customer, with a recommendation for a replacement. He may nevertheless decide to over-ride this advice, because of the need for a quick return to operate vital equipment, but that would be his decision, and at least he would have the opportunity to initiate the procurement of a new replacement later.

In situations of this kind, it would also be an advantage to the customer, if the repair shop had the facility to load-test the repaired motor, and quantify the drop in performance. Testing is covered in a later Section of this Guide.

The Preliminary Inspection is the opportune stage to assess and record damage to components, leading to decisions whether they should be repaired or replaced. These are the questions covered in the next Section.



Ref.	Part Description
1	Endshield, drive end, foot mounted
2	Endshield securing bolts, drive end (Through pins on frames 80/90)
3	Stator frame and windings with or without feet
3A	Facing for top-mounted terminal box
4	Pack peg
4A	Eyebolt
5	Oil seal, drive end (when fitted)
6	Preload washer
7	Bearing, drive end
8	Rotor and shaft
9	Bearing cap non-drive end
10	Bearing, non-drive end
11	Oil seal, non-drive end (when fitted)
12	Endshield, non-drive end
13	Fan cover fixing screws
14	Endshield securing bolts, non-drive end
15	Fan
16	Inner bearing cap screws
17	Fan cover
18	Terminal box lid
18A	Terminal box lid screws
19	Internal earth terminal
20	Terminal box lid gasket
21	Terminal box
21A	Terminal box fixing screws
22	Terminal box gasket
23	Terminal board
23A	Terminal board fixing screws
24	External earth terminal

Fig. 2 Exploded view of motor (reproduced courtesy of Brook Hansen plc).

REPAIR OR REPLACEMENT OF PARTS

Stator cores and windings, rotors, bearings, seals and fans are all covered in other sections of this Guide. The subject of this section is the problems arising when rectifying damaged components, particularly major structural parts such as stator frames and endshields.

The question frequently arises; whether to replace or repair. Factors such as availability, feasibility, cost, timescale and of course reliability, will influence the choice. The concern of this Guide however, is the effect on the energy efficiency of the repaired motor, and this can be impaired in two ways, when repairing or replacing parts:

- high compression stress in the stator back-iron, caused by excessive interference fit between the stator core and the replaced or repaired frame;
- problems caused by eccentricities or other inaccuracies in machining, such as an uneven air-gap, or increased bearing friction.

Considering firstly the stator frame, there are three basic types used in modern induction motors, and they pose different problems to repair shops.

Cast Iron Stator Frames

Fig. 2 shows an example of a motor of cast iron construction.

In large frame sizes, laminations are stacked into the frame piecemeal, and keyed under pressure. In small/medium sizes, pre-built cores of welded or cleated lamination packs are wound, impregnated, then pressed into the frames to light interference fits, and located by dowels. In the case of a damaged stator frame, Best Practice, subject to availability is to fit an identical replacement, supplied by the manufacturer fully machined. This will probably have been done on a machining centre, fixtured and tooled so that spigots and bore are machined to close tolerances at a single setting, to achieve concentricity.

If the only available spare is an unmachined casting, or if the broken casting can be suitably repaired, machining will probably be performed by a traditional method, such as a vertical borer. The following must then be carefully controlled:

- bore tolerance to ensure the correct (light) interference fit;
- spigot tolerances and concentricity relative to the bore;
- correct tolerance on the axial distance between spigot facings, and their perpendicularity.

Aluminium Alloy Stator Frames

Manufacturers' production techniques for stator assemblies with high-pressure die-cast aluminium frames differ from cast iron in several ways. There is much more interference in the fit, to allow for the higher thermal expansion of aluminium. Typically 0.1% difference in diameter ensures that contact is maintained at the highest realistic operating temperatures, but without excessively compressing the back-iron when cold. Hence, frame bores are machined smaller than cast iron, or even "cast-to-size," to eliminate boring. Press fitting with such tight fits is fraught with problems, shrink fitting at about 250° C being preferred. Spigot turning is the final operation, registering from the lamination bore; e.g., on an expanding mandrel.

For the repairer to replace an irreparably damaged frame, a complete replacement stator would generally be the favoured option, if available. Otherwise, whether fitting a new or repaired stator frame, the manufacturers' procedure described above should be followed as closely as practicable, paying particular attention to:

- an adequate, but not excessive degree of interference fit;
- spigot tolerances and concentricity relative to the stator bore;
- correct tolerance on the axial spacing of the spigot facings, and their perpendicularity.

For both cast iron and aluminium frames, it is important to stress the need to remove all baked varnish from the outer surface of the core before refitting. Failure to observe this can affect dimensional accuracy, and also impedes heat flow, causing increased operating temperature and I^2R loss.

Fabricated Steel Stator Frames

In Britain, steel fabrications have rarely been used for stator frames up to 200 frame, but in larger sizes have been significantly exploited in a range of hollow-ribbed frames, resulting in very effective heat dissipation. This construction however, does not facilitate separate frame replacement, as the stator core and frame are welded to each other. In the event of severe damage to either component therefore, the entire stator may need to be replaced.

Endshields

Badly damaged endshield castings may need to be replaced by manufacturers' spares, preferably factory machined.

If unavailable, a decision has to be made between alternative replacements, such as fabricated steel or foundry castings using improvised patterns, or as a last resort, repair of the damaged casting by welding. The latter calls for considerable expertise, and usually requires new metal to be added at machined surfaces, followed by re-machining.

The choice between these alternatives is not the concern of this Guide, provided there is no adverse effect on performance. It is important to ensure correct fit of the bearings, and to have an even air-gap in the re-assembled motor. These requirements call for accurate machining, including concentricity of the spigots relative to the bores of the bearing housings, also perpendicularity of facings and their axial relationship. Best Practice is to machine all these at one set-up.

REPAIRS TO THE ROTOR ASSEMBLY

A common problem is the replacement of a damaged shaft. Less frequent is the incidence of damage to the cage rotor itself. However, as the two parts of the rotor assembly are often difficult to separate, they will be considered as one entity.

If the motor under repair is of current production, and there is irreparable damage to the shaft or rotor core, the preferred option may be a complete new rotor assembly, supplied by the manufacturer. If unavailable, repair or replacement of the damaged component has to be considered.

Damaged Shaft

Taking first the problem of replacing or repairing a damaged shaft, this would not usually affect the energy efficiency of the motor, but certain precautions are necessary.

One method of repairing a shaft with a badly damaged drive-end is to cut off the damaged portion, butt-weld a new extension, and re-machine with the rotor core in-situ. This should have no effect on performance.

If the shaft needs to be removed, this may be relatively simple, if the rotor has been keyed on with a light interference fit, or pressed onto a splined shaft. However, it has become common practice to heat-shrink rotor cores onto shafts, and subsequent removal is then difficult, without damaging the rotor core. It may be advisable to cut off the shaft as close to the core as possible, and carefully bore out the portion of shaft inside the core.

After fitting the new shaft, the outer surface of the core requires checking for eccentricity. A run-out of 0.05% is tolerable, but excessive eccentricity would need correcting in the lathe, using a sharp tool and removing a minimum of material, as increasing the air-gap may reduce motor efficiency. Re-balancing would then be advisable.

For certain corrosive environments, special motors are fitted with stainless steel shafts, and these require particular care in the event of replacement. Some grades of stainless steel are almost non-magnetic, and as that portion of the shaft on which the core is fitted, may lie in the path of the magnetic flux, the use of such steels can adversely affect the motor losses. To prevent this, manufacturers sometimes use normal steel for the internal portion of the shaft, to which a stainless steel extension is butt-welded. Repairers need to be aware of this, when replacing a shaft of this type.

Damaged Cage

Rotors with die-cast aluminium cages rarely fail. When they do, the failue is usually caused by severe and repeated starting conditions, producing cyclic thermal expansions, which ultimately cause cracking at the junction between bars and end-rings. Repairs are impracticable, the only feasible course of action being a replacement, which should be identical in terms of laminations, slot skew, end-ring sections and overall geometry, to restore the motor to its original level of performance.

Rotors with inserted bars of either copper or aluminium, brazed or welded to the end-rings, tend to have higher failure rates than die-cast rotors. Brazed joints which have failed due to over-heating can usually be restored to their original state by re-brazing. Good Practice requires that the bars are held in close contact to the end-rings before brazing, to avoid high resistance joints which would increase rotor losses.

Fabricated cages can also fail mechanically, usually by fatigue breaks, caused by vibrations in loose-fitting bars. When a bar breaks in this way, it is followed by arcing between the bar and the surrounding core steel, which may cause sufficient damage to require a complete rotor re-build. To ensure that the losses are kept to a minimum, the following Good Practices need to be followed when re-building a rotor:

- *replacement laminations, bars and end-rings should be identical to the original;*
- *the skew of the slots should not be altered. (In particular, increasing the skew would increase the rotor losses; decreasing the skew could impair other characteristics, such as noise and starting performance);*
- *bars should be in good mechanical contact with the rings before making the joints (to avoid high-resistance joints, which increase rotor losses);*
- *the rotor should be turned to the same diameter as the original, using a lathe tool with a correctly formed and sharpened tip to minimise surface loss (one of the components of the additional load losses).*

RECORDING THE WINDING DETAILS

An accurate copy of the winding details can only be made, provided that its specification is correctly measured and recorded in detail.

The measuring and recording are carried out as a co-ordinated activity, hand-in-hand with the stripping out of the existing winding. The following is the usual sequence of operations, typically performed by repair shops:

- measurement of the winding overhangs;
- recording the connection details;
- noting the style and configuration of the winding, coil pitches, etc.;
- stripping the winding (see the following section), and setting aside the cut-off non-drive end, and one coil group;
- counting the turns in each coil of the set-aside coil group;
- checking the number of wires in parallel and the diameter of each wire after burning off the enamel.

It is crucial to the success of the repair that this is done with precision, otherwise the performance of the repaired motor is likely to be inferior to the manufacturer's original winding. Verification of winding data by reference to other sources is sometimes advisable. This particularly applies to motors which have previously been rewound, and especially if it is suspected that the winding configuration has been changed from the original.

Winding Database

It is good practice to establish a database of standard motor windings, from the repair shop's own job-experience and/or from information furnished by manufacturers. Such a database is available from the AEMT. If winding information is not available in-house, for example if the motor is non-standard, it can often be provided via fax or telex by the manufacturer's technical department. Such verification can avoid copying any mistakes made during an earlier rewind.

PAM Windings

Copying PAM windings calls for particular care. These speed-change windings are a special case, as their coil groupings are so irregular as to appear chaotic to a rewinder with no previous experience of them. Unless details of the complete winding specification can be obtained from the manufacturer, the only solution is a meticulous coil-by-coil check of all groupings and connections.

STRIPPING THE STATOR WINDING

The condition of the stator core and frame after the stripping process has been completed should be such that no damage has been sustained which could be detrimental to motor performance. Any damage may be either mechanical or thermal.

Mechanical damage can include gashed teeth caused by the tools used for cutting off the end windings, and bent teeth incurred whilst pulling out the coils. The manufacturer will have used steel laminations in a fully softened state after final annealing, in order to minimise core loss. Any subsequent bending of the steel sets up internal stresses, which cause local increases in core loss. No matter how carefully the teeth are bent back into shape, the original state of the steel cannot be restored (except by re-annealing). Indeed, hammering them back into shape work-hardens them even further. It is also time-consuming.

Thermal damage can result from the excessive application of heat prior to coil-pulling. This does not affect the steel itself, but can damage the insulating surface film separating adjacent laminations, again causing increased core loss.

The effects of thermal damage are described more fully in Appendix2.

Damage of one form or another can be inflicted during any of the three essential stages (A, B and C) of the stripping process, described below. However, the use of good practices performed with care can avoid such damage completely.

Previous Repairs

Damage as described above may already have been inflicted during a previous repair. By observation, it is usually possible to recognise a previously rewound motor, and the use of a stator core tester can generally detect whether the core pack is still sound (see under “Cleaning and Inspecting the Stripped Stator”). Otherwise, if there are doubts about the stripping process previously used, it is the duty of the repairer to inform the customer that the energy efficiency after repair may be inferior to that of the motor as originally supplied.

The effect of successive rewinds is covered in Appendix 2.

Stage A
Cutting off one of the end windings (usually the connection end)

The objective is to achieve the cut as close to the end of the core pack as possible without damage to the end laminations, and with minimum distortion of the severed wires, so that they will subsequently pull out without disturbing the teeth.

Methods used include hand-held or powered chisels, also hand-held rotary cutters fitted with either toothed or abrasive discs. Such methods can give good results when skillfully performed, but *Best Practices are those which achieve the objective with minimum emphasis on operator skill.* In one example, the stator is clamped on a plate and rotated on its own axis, whilst a high speed cutter, accurately set to a minimum clearance from the end of the core, is fed into the coils.

Stage B
Releasing the varnish bond

Although coils can sometimes be pulled out without any such process, mechanical damage can best be avoided by first weakening the varnish bond, either by chemicals or by the application of heat.

The otherwise successful use of powerful synthetic agents such as trichlorethylene vapour has been discouraged in recent years, due to Health and Safety considerations and environmental problems. Another chemical method is the use of caustic liquids, but these also are hazardous and can leave harmful residues trapped between laminations, which are difficult to remove.

Burn-out Methods

Burn-out methods have therefore become most favoured, generally gas fuelled, and purpose-built proprietary ovens are available which are temperature-controlled, and provided with after-burners to render the exhaust fumes environmentally acceptable. However, less sophisticated equipment is also in use.

It is outside the remit of this Guide to state preferences based on environmental considerations. The key objective is to effectively loosen the varnish bond, without detriment to the core losses, and to this end, when using any burn-out method, core pack temperature limitation during the process is paramount. (See Appendix2.)

It is therefore strongly recommended, based on the results of an AEMT research project, that the core steel temperature should not be permitted to exceed 360° C during the burn-out process. Best Practice requires that this is controlled by a reliable temperature monitor, periodically calibrated.

This subject is more comprehensively treated in Appendix2, which includes a report of the research project. It must be emphasised, however, that the AEMT research work so far has been restricted to relatively small motors; therefore the recommended limit of 360° C is at present applicable to motors up to and including 180 frame sizes (22 kW rating). Until the research can be extended successfully through larger motor sizes, specific burn-out temperature limits cannot be included in this Guide for frame sizes larger than 180 incorporating oxide-coated core steel.

There is a significant exception to the above burn-out temperature restrictions. An important development in core steels coated with heat resistant varnish enables burn-out at even higher than 360° C without detriment, regardless of motor size. This also is included in Appendix2.

Possible damage to the core pack is not the only reason for prevention of excessive temperatures during the burn-out process. There is also the possibility of damage to the stator frame, particularly when this is of aluminium alloy. With some methods of heating, the frame may attain a higher temperature than the core steel, with danger of distortion leading to air-gap eccentricity in the re-assembled motor.

Stage C
Pulling out the coils

During coil extraction, frictional drag inside the slots can bend the teeth of the end laminations, particularly if there are any bent wires at the cut-off coil ends. It is therefore good practice to use fixtures which support the tips of the teeth at the end of the core during coil-pulling.

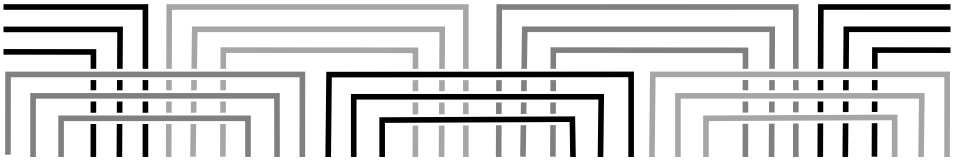


Fig. 3 36 slot 4 pole 2-tier concentric winding

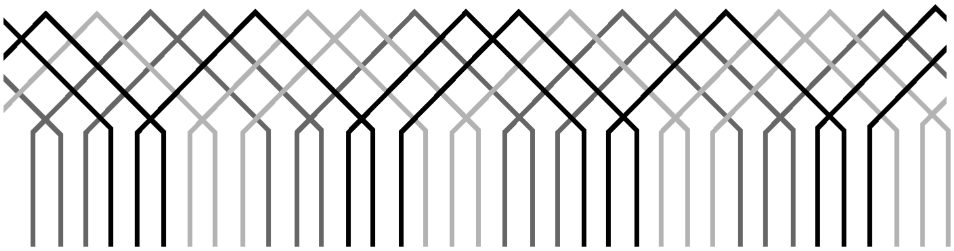


Fig. 4 36 slot single-layer lap winding, pitched 1-10

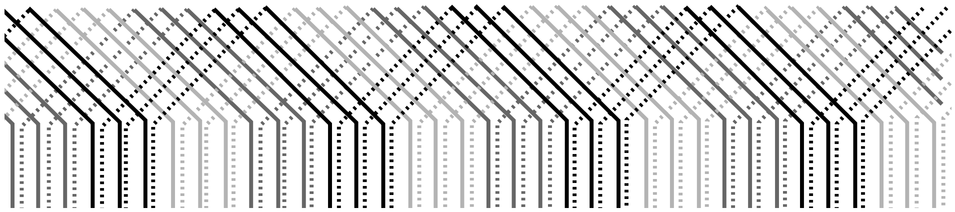


Fig. 5 36 slot double-layer lap winding, full-pitched 1-10
Note that the windings illustrated in Figs. 3, 4 and 5 result in exactly the same distribution of phase bands in the slots; i.e., 12 bands of 3 slots each.

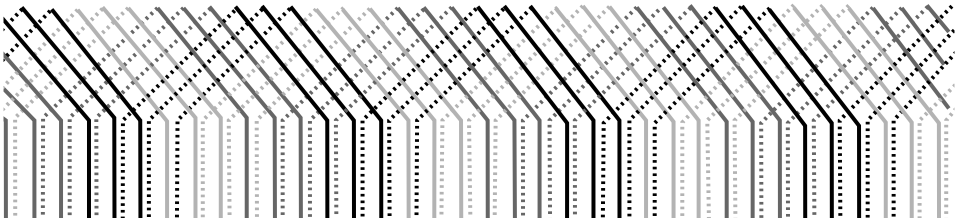


Fig. 6 36 slot double-layer lap winding, short-pitched 1-9
Note that due to some slots being shared by coil sides of different phases, the phase bands are each spread into 4 slots in a sequence half-full-full-half.

SPECIFYING THE REPLACEMENT WINDING

In specifying the replacement winding, to ensure that the motor performance will match that of the original winding, there is always one obvious choice, namely to copy exactly the original in every particular. This would include not only the conductor size and the number of turns, but the style of the winding, its configuration, and exact shape of the coils.

This simplistic approach is always possible, and virtually guarantees satisfactory results, but is not always the most convenient. This is because of the differences between the manufacturers' methods of winding stators and those used by repair shops.

In the motor manufacturing industry, modern developments in stator winding by the so-called "coil-shooting" method embrace stators up to frame size 250. At the high volume end of the range in the latest technology the entire sequence of operations is performed in an automated sequence, including coil winding, coil insertion and pressing of the coils into shape, within a cycle time of only a few minutes. The operation is highly capital-intensive, using a minimum of labour.

As a result of these developments, more than 90% of induction motors up to 75 kW are now machine-wound, and these constitute the majority of motors appearing in repair shops for rewinding. Now the only types of winding that these machines can produce are those in which the coils are in concentric groups, each group comprising coils having different spans.

Although windings of this type can be reproduced by hand-winding techniques, repair shops generally prefer to use winding configurations in which all the coils are identical, so that a single coil-former can be used. It is therefore important to consider what effect on motor performance would result from the substitution of concentric windings by types of winding employing single-span coils.

A detailed discussion in principle of winding changes and their effects is given in Appendix1, and the manner in which these relate to specific winding substitutions is given below.

There are in fact three basic configurations of concentric windings which need to be considered separately.

2-Tier Concentric Windings

This is not a practicable method of winding 2 pole stators, neither is it used for winding 6 pole stators as it results in assymetry due to the odd number of coil groups. It is however the configuration most favoured for the 4 pole high volume end of the range, particularly 36 slot windings up to and including 132 frame sizes, and is illustrated in Fig. 3.

As rewinds, either single-layer full-pitched lap windings (see Fig. 4) or double-layer full-pitched lap windings (see Fig.5) are straightforward substitutions, producing in both cases unchanged distribution of conductors per phase in the slots. Providing the turns per slot, wire size and length of mean turn (LMT) are unchanged, the performance should closely match the original.

If the double-layer lap configuration is selected, the option of short-pitching the coils enables three further advantages to be gained, as explained in Appendix 1: (a) a reduction in the ammount of copper, (b) reduced I^2R loss, and (c) an improved distribution of the air-gap flux.

For example (see Fig.6), a 4 pole 36 slot winding could be chorded one slot by pitching 1-9. This reduces the effective number of turns, which theoretically requires correction by a slight increase (1.5% in this example), but this only slightly offsets the significant advantage of 11% reduction in end-winding copper.

This was recently demonstrated in a collaborative project involving a manufacturer and a repairer. Four 2-tier concentric wound stators were rewound double-layer, and the effect on performance measured by the manufacturer. The two rewinds pitched 1-10 showed only marginal changes (in fact slight deterioration), but the other two, pitched 1-9, had approximately 0.5% improved efficiency.

However, there may be a problem in substituting a double-layer winding if the original is fairly tight in the slots. The need for the additional in-between insulation increases the slot-fill factor.

Summarising, a 2-tier concentric winding can be replaced by either:

- a full-pitch single-layer lap winding, without loss of performance;
- a full-pitch double-layer lap winding, without loss of performance;
- a short-pitched double layer lap winding, with the possibility of reduced end-winding copper and enhanced performance.

3-Tier Concentric Windings

The attraction of this style of winding is its economy in copper, due to its shorter average coil span compared with the 2-tier equivalent. This is illustrated by Figs. 7 and 8. In the high-volume production of small 4 pole motors, this saving in material is not sufficient to offset the increase in machine winding costs. However, in the relatively low volume production levels of 4 pole 160 frames and larger, particularly when the stators have 48 slots or more, the overall cost appears to favour the 3-tier winding, which is becoming more popular in these sizes. In addition, 3-tier windings have a particular advantage for 2 pole and 6 pole motors, for which 2-tier windings are impracticable to produce by the coil-shooting technique.

When rewinding 3-tier concentrics, the problem of substituting an equivalent single-span type of winding presents a more difficult problem to the repairer. The best way to illustrate this is to consider a particular case. For example, a 48 slot 3-tier concentric winding has 12 coil groups of 2 coils each, pitched 1-10 and 1-12. Thus the average pitch is 1-11, whereas a lap wound stator having exactly the same distribution of conductors in the slots would have coils pitched 1-12 if single layer, or 1-13 if double layer. Hence the individual coils of the replacement lap winding would have a greater span than the average coil of the 3-tier.

Obviously, unless the coil formers of a 3-tier winding are carelessly designed in the first place, a replacement full-pitch lap winding is almost certain to contain more copper. To overcome this disadvantage, a short-pitch lap winding can be considered; for example, double-layer pitched 1-11. However, this would need an increase in turns to compensate for the pitch-factor, the compensation in this particular example being 3.5%, which would offset some of the copper saving achieved by the shorter span.

The above emphasises the particular advantage of 3-tier concentric windings. Firstly, they are economical in copper, and secondly, as they employ less copper they also generate less copper loss.

Summarising, 3-tier concentric windings are particularly economical in copper and generate relatively low copper loss. These characteristics are difficult to match by substituting other winding configurations, although a short-pitch double-layer lap winding (suitably compensated) might be acceptable.

The Best Practice, however, is probably an exact copy rewind.

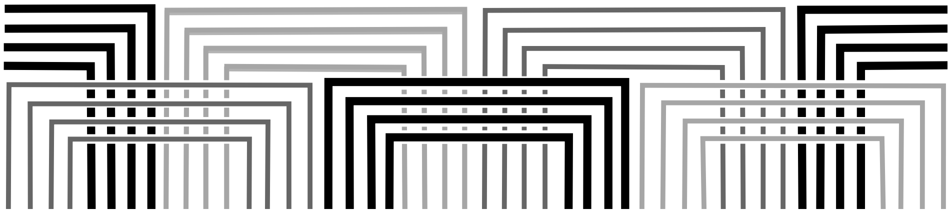


Fig. 7 48 slot 4 pole concentric 2-tier winding

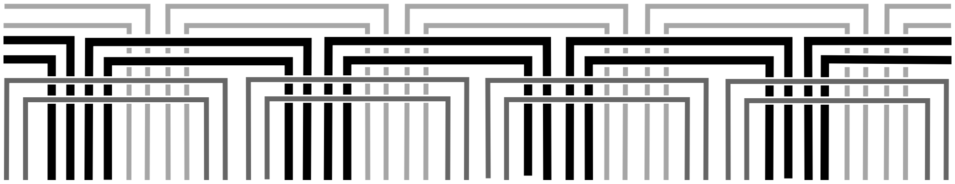


Fig. 8 48 slot 4 pole concentric 3-tier winding
Note that this winding results in an identical distribution of phase bands in the slots as Fig.7, but achieved with an average coil span which is 2 slots less.

Double-Layer Lap Winding with Concentric Groups

This winding configuration has become popular for larger motors (frames 225-355) as it enables the winding operation to be "machine assisted," using a type of machine developed in the 1980s.

Typically, a 4 pole 72 slot stator with 12 coil groups of 6 coils per group may have coil pitches of, say, 1-21, 1-19, 1-17, 1-15, 1-13 and 1-11 (see Fig. 9). When rewinding such a motor, a repair shop would generally prefer to substitute a normal double-layer lap winding, each coil being pitched equal to the average coil pitch of the concentric group, as this requires only one coil former. In the above example the average coil pitch is 1-16, and a double-layer lap winding pitched 1-16 (i.e., chorded 3 slots) with the same turns per coil would match its performance, provided the LMT does not exceed the average of the concentric group. This should not be difficult to attain.

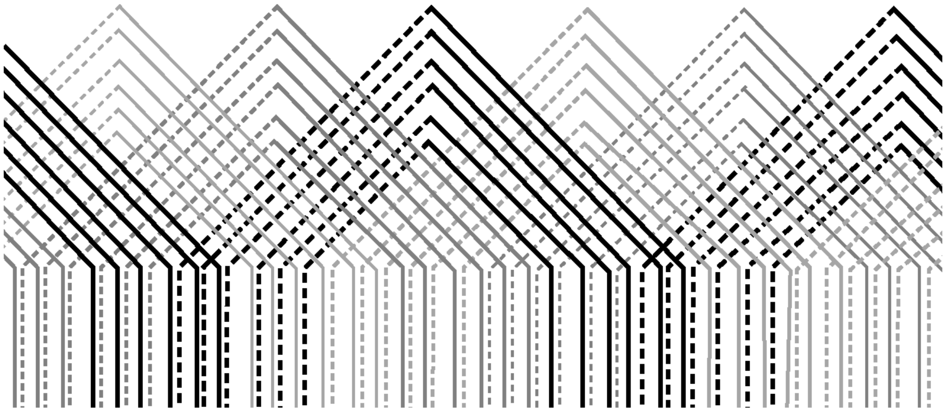


Fig. 9 4 pole double-layer concentric-grouped lap winding
(Only part of the winding is illustrated here).

Rewinding Lap-Wound Stators

General recommendations for rewinding these are as follows:

- it is not good practice to replace double-layer lap windings with single-layer windings, particularly if the double-layer winding is short-pitched. The performance would generally be reduced, both in efficiency and in starting torque. An exact copy therefore constitutes Best Practice;
- a single-layer lap winding may be rewound as an exact copy, but the performance can be improved by substituting a double-layer lap winding, short-pitched approximately one sixth of a pole pitch (to the nearest whole slot). Obviously, this requires the usual small increase in turns to compensate for the pitch-factor, and before making the decision to do this substitution, it is prudent to check that the slot-fill will allow the inclusion of the in-between insulation and the additional turns.

CLEANING AND INSPECTING THE STRIPPED STATOR

Cleaning

As a result of the burn-out process, semi-burnt deposits of varnish or other insulating materials often remain as adhesions on the core-pack surfaces, particularly inside the slots. If after inspection it is necessary to remove any such deposits before rewinding, methods are preferred which will not increase the core-losses.

Gas-fuelled torches specifically designed for insertion into the slots, and used in conjunction with an oxygen pistol or probe, provide an effective method of burning off deposits, and are so quick acting, that local over-heating of the core-steel is avoided.

Files and/or abrasive tools should only be used with extreme caution. The creation of burrs around the edges of laminations is a possible cause of short-circuit paths for additional eddy-currents. Damage to the tooth tips can have a particularly adverse effect on efficiency.

Inspection

If, notwithstanding the care taken to avoid damage during the stripping process, damage is found to have occurred to the teeth of the end laminations, these need to be repaired, using a minimum of mechanical force. In particular, excessive hammering of bent teeth into submission can set up compressive stresses, not only in the teeth of the end laminations, but in the plates behind them, causing increased core loss. Minimum impact should be applied, preferrably using a soft-faced mallet rather than a steel hammer.

In cases where the motor failure was caused by a short circuit or earth fault inside a stator slot, the protective devices in the circuit may have been inadequate to prevent thermal damage to the core-steel in the vicinity of the fault. This may be revealed by a visual inspection.

Proprietory or purpose-built core-loss testers can be useful tools for checking the general quality of the stator core, particularly for deterioration of the inter-lamination insulation resulting from excessive temperatures during the burn-out processes. However, these devices operate by using the stator back-iron as the core of a transformer, and during the test negligible flux is established in the teeth. This obviously limits their effectiveness in checking the presence of hot spots in the teeth area.

Only a final no-load test on the assembled motor after rewinding can provide definite data of motor core loss. Therefore if there is doubt about the stator core quality, without the benefit of a core-loss tester, it is advisable to consider replacement.

REWINDING

By the time this stage is reached, the replacement winding has been specified; therefore most of the decisions affecting the motor losses have already been made. However, there is one important detail which is generally left to the winder, namely the setting of the coil shape and dimensions. Unless this is done intelligently, the copper loss can be increased.

It has often been said that the end windings consist of “inactive” copper, merely serving to span between the “active” conductors or coil-sides inside the slots. However, in the majority of stator windings, especially of 2-pole and 4-pole motors, the end winding copper weight exceeds that of the copper in the slots, and therefore has a dominant contribution to the total stator copper loss.

Minimizing the End Winding Copper

It is very important, therefore, that the end winding copper is kept as short as possible. If the L.M.T. (length of mean turn) of the rewind exceeds the original, the copper losses will be increased. Attention to the following rules will prevent this:

- *keep the winding overhang within the measured dimensions of the original winding;*
- *do not extend the slot insulations beyond the slot ends any more than is necessary to form an effective “cuff”;*
- *do not extend the straight portions of the coil sides any further than is necessary to clear the slot insulations;*
- *in the case of lap-windings, consider diamond shaped coils in preference to rounded ends, with the largest possible angle, consistent with inter-coil clearance. In the case of concentric windings, minimise the length by means of generous radii, particularly in the outer coils.*

There is, of course, an obvious additional incentive to the repairer to minimise the L.M.T.; it reduces the cost of the materials, but there has to be a compromise. If the coil ends are too short, accommodation into the end windings becomes difficult (or impossible) by lack of space, and the additional winding time can offset any material cost saving.

However, by careful specification of the winding and coil dimensions, it is always possible to equal or improve the performance of the original winding in regard to copper loss.

TESTING THE WOUND STATOR

Routine test schedules employed by repair shops vary in scope, but typically include a selection from the following:

- resistance measurements of all three phases, together with a reading of the ambient temperature;
- an insulation resistance ("Megger") test;
- a high-potential ("flash") test of the insulation to earth, at 2000 volts minimum. If the three phases are separately terminated, it is usual to test each phase separately to earth, and to test the insulation between pairs of phases;
- surge test; a recurring steep-fronted high voltage surge is applied to the separate phases in pairs, the resultant currents being superimposed and displayed on an oscilloscope. This sensitively detects phase imbalance caused by unequal turns, reversed connections, insulation failures, etc.

It is appreciated that the essential purpose of the routine test schedule is fault detection, as corrective action is much easier to perform before impregnation.

The Purpose of this Guide

The purpose of this Guide, however, is to ensure that the energy efficiency of the motor is maintained. In this context, there is one of the above tests which is especially relevant. The measurement of stator resistance can provide a direct indication of the stator copper loss. It can give proof whether this has been affected by the rewind, particularly if the resistance value of an identical motor is available from a data file.

Resistance measurements are therefore considered an important inclusion for Good Practice procedures, whether it is included at this stage, or in the final test of the assembled motor.

IMPREGNATING AND CLEANING THE REWOUND STATOR

Impregnation

Motor manufacturers in general have retained the traditional dip-and-bake method of stator impregnation for volume production of motors larger than 90 frame, as being the most cost-effective. Many repair shops, on the other hand, have changed to trickle-feed techniques, generally using two-part epoxy varnishes.

Motor efficiency is not affected by the type of impregnation as such, but the condition of the stator bore and the machined spigots and faces of the stator frame can cause problems in the re-assembly, which affect motor performance. These problems differ according to the method of impregnation employed.

The differences need to be emphasised. During manufacture, the impregnation is usually performed on the wound stator before being inserted into the frame, so that no varnish is applied to the frame, and the machined spigots remain clean. In repair shops, however, the rewound stator is impregnated with the frame in-situ, as it is impracticable to remove a cast-iron frame, and impossible to remove a shrink-fitted aluminium frame without damage.

This is one of the reasons why many repair shops have changed to trickle-feed impregnation, in that any problems caused by varnish being applied to the surfaces of the frame are avoided.

Cleaning the Impregnated Stator

A film of varnish baked onto the spigots and facings can obviously affect the fit of the endshields, and cause eccentricity of the air-gap and bearing misalignment. A thin, uniform film of varnish in the stator bore is not a problem, but runs or “tears” and particularly pools collecting on the bottom of the bore can cause rubbing of the rotor after assembly.

In the case of stators which are being varnish-dipped, it is good practice to allow an adequate draining period before loading them into the baking oven, so that surplus varnish can drain away. The problem surfaces should then be wiped clean with a solvent-soaked rag prior to baking.

Even so, some further draining of varnish during the early stage of baking is likely, and requires subsequent removal by scraper or abrasive tool. In doing so, over vigorous use of the tool is to be avoided, to prevent damage to the metal surfaces, particularly the relatively soft machined surfaces of aluminium alloy frames, and of course to the edges of laminations in the stator bore.

With trickle-impregnated stators, it is unlikely that there will be any varnish deposit on the spigots, but varnish can seep out of the slot openings of the stator bore, requiring similar attention to dipped stators.

RE-ASSEMBLY

There are several important precautions which are necessary in the re-assembly operation, to ensure unimpaired motor performance.

Cleanliness

The removal or exclusion of foreign bodies is so obvious a requirement, that mention of it may seem superfluous, but by default is the cause of many motor problems. Failure to detect metal turnings, drillings, loose pieces of insulations, etc., can lead to them becoming lodged in the air-gap to set up additional frictional losses.

Safeguards include prior use of bead blasting and/or washing of components, and rigorous visual inspection and blow-out by compressed air.

Uneven Air-Gap

Eccentricity of the rotor relative to the stator bore has the effect of distorting the magnetic flux in the air-gap, and increasing the core loss and the additional load (“stray”) losses. It also produces unbalanced magnetic pull, causing mechanical deflexions which further increase the eccentricity.

In extreme cases, the more serious condition can occur, of rubbing of the rotor in the stator bore, generating additional friction losses, leading to probable failure.

Air-gap concentricity depends on the dimensional accuracy of a number of components, namely the stator core, the frame, the endshields, the shaft and the rotor core. Inaccuracies in these affect the uniformity of the air-gap, and since all of them are subject to manufacturing tolerances, it follows that some air-gap eccentricity can be expected even in new machines, to a degree which depends on the effectiveness of the manufacturer’s quality control.

The situation can be exacerbated by “wear and tear,” and it is important that the repairer examines the key components at the initial inspection stage, particularly for cracked or distorted castings, or other accidental damage requiring remedial attention or replacement.

In addition, there is the possibility that the eccentricity can become worse as a result of the repair operations themselves, unless good practices are employed with proper care. Some of these are listed below.

- distortion of the frame, particularly if it is of aluminium alloy, can be caused by excessive temperature during the burn-out process prior to stripping the winding. This can be minimised by working within the maximum temperature recommended in Appendix 2;
- deposits of varnish on faces and spigots during impregnation, if not carefully removed, will affect the fit;
- distortion of endshields (if made of aluminium alloy) can be caused by heavy handed methods during assembly. A few persuasive taps with a soft-faced mallet are adequate to fit the bearing housing on to the outer race of the bearing, and to engage the spigots into the frame.

It is not good practice to increase the air-gap. This increases the stator current, reduces the power factor, and usually reduces the efficiency. Nevertheless, if the rotor core is found to have been eccentrically turned in relation to the shaft, it is prudent to take corrective action by a light skim in the lathe, removing a minimum amount of metal. It is particularly bad practice to machine the stator bore. This can cause short circuits between laminations at the tooth tips, made even worse by the need to de-burr the slot openings, and leads to increased core loss.

Bearings

Worn, damaged or ill-fitted bearings can generate additional friction loss. Faulty bearings must of necessity be replaced, but it is common practice in many repair shops to use the repair as an opportunity to renew life expectancy by routinely fitting new bearings. These of course must be of equivalent specification to the originals.

Mis-alignment of the bearing housings can be minimised by the same precautions as listed above (under the heading “Uneven Air-Gap”). Correct seating of the bearings on the shaft is ensured by the use of bearing drawers to remove the old bearings, and by shrink-fitting the replacements, rather than forcing them on cold. The use of electro-magnetic bearing heaters (auto-controlled to avoid bearing damage due to over-heating) constitutes good practice.

The axial location of the bearings requires care during re-assembly. Motors are designed so that one or both bearings have a degree of freedom of axial movement within their housings. For example, one popular arrangement features a ball-bearing at the non-drive end which is positively located both on the shaft and within its housing. In contrast, the drive end ball-bearing is positively located on the shaft, but has space for axial movement within its housing, where a wavy pre-loading spring washer (see Fig. 2, Ref. 6) is included to give quieter operation.

Other bearing arrangements are in use, but in all cases it is important that the designed axial clearance is maintained; otherwise, “double location” can occur, causing uncontrolled end thrust which may increase as the shaft heats up, producing extra friction and reduced bearing life. Causes of this include incorrect positioning of the bearings on the shaft, wrongly specified preload washers, shafts and/or housings machined to incorrect tolerances, etc.

Shaft Seals

In recent years, oil seals have been fitted increasingly as a means of achieving IP55 protection in standard motors.

Worn or damaged seals need replacing with the correct type, and as in the case of bearings, routine replacement is the policy of many repairers. The best method is to avoid distortion by pressing them evenly into position, and to ensure that the sealing surfaces are well lubricated.

Cooling Fans

In older designs, the cooling fans of small/medium motors were often relatively large, to maximise the cooling air velocity for maximum cooling effect. In totally enclosed motors they tended to occupy practically all the available space inside the fan cowl, and contributed significantly to the energy losses. The exceptions were 2-pole motors, which were often fitted with smaller fans to reduce noise emission.

In current designs, in which energy efficiency has become a design objective, the fact that there are fewer watts of energy loss to dissipate has enabled smaller fans to be employed, even in 4 and 6-pole motors, etc., whilst 2-pole fans have gone even smaller.

The fan design is a compromise between the conflicting requirements of effective cooling and low windage loss, and it is most important that if a motor undergoing repair requires a replacement fan, it should be of the correct size. An identical replacement of course is ideal, but if unavailable, a near match may have to be substituted. If so, it needs emphasising that any increase in outside diameter has a much greater effect than either the axial length or the number of blades. It is the outer part of the blade that produces most of the air displacement; therefore the replacement preferably should be not greater in outside diameter than the original.

TESTING THE ASSEMBLED MOTOR

No-Load Tests

Traditionally, routine tests carried out on every repaired motor include:

- static tests: 2 kV applied between winding and earth to verify the soundness of the insulation, and measurement of the winding resistance;
- a no-load run at rated voltage, with measurements of line currents and rev/min., and subjective observations of noise and vibration. An extended run of 5 to 10 minutes is advisable, to ascertain that replacement bearings and seals do not over-heat.

These tests serve their purpose of checking that the winding is correct, and the motor is mechanically and electrically sound. *They give no indication of its energy efficiency.* However, by including wattmeter readings in the no-load test, the no-load losses can be measured, and by deducting the no-load I^2R, the constant losses can be calculated. It would be good practice, therefore, to include this additional feature in the routine test, and to monitor the no-load or constant losses for verification purposes.

Locked Rotor Tests

As a back-up to the no-load running test, measurement of the line currents with the shaft locked, when connected to a 3 phase supply of 25% of rated voltage, serves to confirm that the motor has been correctly rewound. However, a variation of this test is particularly useful for checking the soundness of the cage rotor. By applying a single phase supply to the stator and slowly turning the shaft, a cyclic variation of the line current as the rotor moves through one pole pitch would indicate a faulty cage.

Load Tests

In view of the purpose of this Good Practice Guide, namely to maintain the energy efficiency of motors undergoing repair, the Repairer needs to consider setting up a load-test facility to measure the efficiencies of repaired motors.

This is not intended to imply that load-testing should be an integral part of the repair process. On the other hand, customers may wish to specify it as an optional extra, including the provision of a Test Certificate.

The principal advantage of the facility, however, is to provide the repairer with an investigative tool. For example, in cases of doubt it provides test data of the losses in the stator core and in the cage rotor, both of which are difficult to quantify by static tests.

Choice of Method

Two basic methods of testing induction motor efficiencies which are recognised by BSI, IEC and the National Standards of most foreign countries are suitable for repair shop application. These are:

Loss Summation

(1) The Summation of Losses Method. In this method a load is applied to the motor shaft, but is not directly measured. The elctrical power input is measured, and the constant losses (core losses, friction and windage), the stator copper loss and the rotor I^2R loss are all determined by a combination of measurements and calculation. The additional load losses, however, are not measured, but empirically estimated.

Hence, having measured the input power, and determined the various component losses, the efficiency is calculated by expressing the Input minus the Summated Losses, as a percentage of the Input Power.

Output/Input

(2) Direct Output/Input Measurement. The mechanical Output Power is measured on a dynamometer, and expressed as a percentage of the electrical Input Power.

The latter method has certain points in its favour, particularly its basic simplicity, plus the fact that the total losses including the additional load losses are taken into account. However, it requires a high level of accuracy in the measurements. For example, a 1% error in both the input and output measurements could cause a combined error of 2% in the measured efficiency. In the case of a motor of, say 90% efficiency, this would represent a considerable discrepancy, considering that it would be 20% of the motor losses.

Of course, instruments and dynamometers of high accuracy are available, but are expensive. Also the range of a dynamometer is limited, so that several may be required, depending on the range of motor ratings to be covered. This level of investment may be difficult to justify unless the through-put is large.

In method (1) Summation of Losses, the measurement of output power is eliminated entirely, and inaccuracies of, say 2%, in the measurements of the losses in the above example would cause a discrepancy of only 0.2% in the motor efficiency. Investment costs are relatively low, the favourite loading devices being second-hand DC generators, belt-driven for convenience. The efficiency calculations are more protracted than in the simple direct method, and used to be considered time-consuming, but with the aid of a programmed PC, the test data can be quickly processed, and the results presented in a printed format.

A further benefit of the Summation of Losses method is that it presents in fact, a breakdown of losses into components. A weakness often quoted by its detractors is that additional load losses are not included in the measurements, but are assigned an empirical value. However, any variation in these caused by the repair is in practice minimal.

Summarising, the Summation of Losses method offers an accurate method of determining the various components of losses in induction motors, and hence the energy efficiency. The method enjoys national and international recognition. The results are more informative than those provided by the alternative Direct Test Method, and the equipment is considerably lower in first cost. Processing of the test data and presentation of the results can be conveniently performed on a PC. The method has much to commend it for use by Repair Shops.

The test procedure and steps in calculation are given in Appendix3.

APPENDIX 1

WINDING VARIATIONS: THEIR EFFECT ON PERFORMANCE

The section entitled “Specifying the Replacement Winding” offers advice to the repairer, who for practical reasons of convenience chooses to substitute a winding which differs in configuration from the original.

This Appendix explains the basis for some of the advice included in that section. It shows how changes in the winding can affect the magnitude of the magnetic flux in the motor, and explains how they influence its performance, particularly the energy losses and efficiency.

The Effect of Winding Changes on the Flux

The voltage applied to each phase is opposed by (and is almost equal to) the electro-motive-force (or “back e.m.f.”), which is expressed in the well-known e.m.f. formula for alternating current machines:

(1) $E = 4.44 f N \Phi K_d K_p$

In the context of a motor undergoing a repair, three of the symbols in the formula can be considered as constants, namely:

E, the phase e.m.f., which is virtually constant if the supply is unchanged; likewise:

f, the frequency, and

K_d, the winding distribution factor, which depends on the slots per pole per phase, and is unlikely to be changed.

This leaves 3 variables under the control of the repairer, namely:

N, the number of series turns per phase;

Φ, the magnetic flux per pole; and

K_p, the pitch factor.

Obviously, the product of these 3 variables must be a constant in order to satisfy equation (1), thus giving rise to the following important rules:

(2) *Increasing either the turns or the pitch factor reduces the flux.*

(3) *Reducing either the turns or the pitch factor increases the flux.*

(4) *Any change in the pitch factor, if compensated by an inversely proportionate change in the number of turns, ensures that the flux per pole remains unchanged.*

The Pitch Factor, K_p

Basically, this is defined as the factor by which short-pitching each coil of a lap winding would reduce the e.m.f., assuming the flux per pole was unchanged.

$$K_p = \frac{\text{e.m.f in a short-pitched coil}}{\text{e.m.f. in a full-pitched coil}}$$

Obviously, $K_p = 1$ when the coils are fully pitched, and is progressively reduced as the pitch is reduced. Mathematically, it can be evaluated from the formula:

$$K_p = \text{Cosine}\left[\frac{\text{pole pitch - coil pitch}}{\text{pole pitch}} \text{ x } 90^\circ\right]$$

For example, a 4 pole 48 slot winding has a pole pitch of 12 slots, and a full-pitched coil would therefore span 12 slots (pitched 1-13). If the pitch was reduced by 2 slots, so as to span 10 slots (pitched 1-11), the pitch factor would be:

$$K_p \quad = \quad \text{Cosine} \left[\frac{12 - 10}{12} \text{ x } 90^\circ \right] \text{ i.e., Cosign } 15^\circ \text{ or } \underline{0.966}$$

Evaluated pitch factors for commonly occurring coil pitches in double-layer lap windings are tabulated below:

Table C. Examples of Pitch Factors

Pole pitch (slots)	**Coil pitch**	**Pitch factor K_p**	**Pole pitch (slots)**	**Coil pitch**	**Pitch factor K_p**
6	1-7 1-6 1-5	1.0 0.966 0.866	9	1-10 1-9 1-8	1.0 0.985 0.94
12	1-13 1-12 1-11 1-10	1.0 0.991 0.966 0.924	15	1-16 1-15 1-14 1-13 1-12	1.0 0.994 0.978 0.951 0.913
18	1-19 1-18 1-17 1-16 1-15 1-14	1.0 0.996 0.985 0.966 0.940 0.906	24	1-25 1-24 1-23 1-22 1-21 1-20 1-19	1.0 0.998 0.991 0.981 0.966 0.947 0.921

The Benefits of Short-pitched Lap Windings

As mentioned in the section headed "Specifying the Replacement Winding," the most common change is from a concentric winding to some form of lap winding, primarily for the repairer's convenience. If the change is to a full-pitched winding, the effect on performance should be insignificant, but the alternative of substituting a short-pitched (or chorded) double-layer lap winding can prove advantageous, and is the type of change particularly considered below.

The potential advantages compared with full-pitched alternatives are as follows:

It provides scope for reducing the length of mean turn (L.M.T.), which saves copper and reduces I^2R loss, despite the need to compensate the reduced K_p factor by a small increase in the number of turns.

Some slots are shared between coil sides of different phases, thus causing overlapping between adjacent phase-bands, to the benefit of the air-gap flux pattern. This improves starting performance and reduces stray losses.

The degree to which the coils are short-pitched involves compromise, as excessive chording reduces (or even reverses) the benefit. According to one criterion, short-pitching the coils by one seventh of the pole pitch optimises the advantage, but of course is not often possible, as the number of slots per pole is rarely a multiple of 7. A rule of thumb favoured by some designers is to shorten the pitch by not more than one fifth of the pole pitch, but as closely as possible to one seventh.

The Flux per Pole: How Changes Affect Motor Performance

Any change in the value of the flux resulting from a winding modification influences significantly almost every aspect of motor performance. For example, the starting torque and starting current are each proportional to Φ^2.

This Guide, however, is particularly concerned with the motor losses, separate components of which are affected by changes in the flux in different ways, as follows:

Total Core Losses: approximately proportional to Φ^2.

On-load Rotor I^2R: inversely proportional to Φ^2.

On-load Stator I^2R: varies in a complex manner in relation to the flux. (An increased flux is generally caused by a reduction in the turns or the coil-pitch, either of which would reduce the winding resistance. The current, however, would increase, but disproportionately, to a degree dependent on the magnetic saturation.)

With such diversity in the variation of the above three components, it is obvious that the effects of flux changes on the total losses do not follow a simple pattern, and are best depicted graphically. As a typical example, Fig. 10 shows the efficiency curve of a 15 kW motor, and how it would be affected by changes in the level of flux.

Generally, in an optimised design, the peak efficiency is attained at (or approaching) full load. Reducing the flux moves the peak of the performance curve away from full load, whilst improving performance at light loads. An increased flux, on the other hand, improves the overload band of performance but reduces efficiencies in the operating band between no-load and full-load.

Thus, unless there is a request by the customer for a deliberate alteration to the motor's characteristics, it is advisable when changing a winding specification to ensure that the flux per pole is not affected. This can be ensured by observance of rule (4) quoted earlier in this Appendix.

Deliberate Changes to Motor Characteristics

The foregoing has emphasised the importance of keeping the flux constant, on the assumption that the motor's performance is not required to change. However, sometimes a repairer may deliberately change a motor's characteristics.

For example, if it is known that a particular motor generally runs underloaded, there may be a case for an increase in the turns to reduce the flux, thus improving efficiencies in the operating range, even though the efficiency at the motor's rated load would be reduced (as also would be the starting torque). Obviously such a change would require agreement by the user, and if in doubt, consultation with the manufacturer.

In general, however, repairers are advised that whenever they change winding specifications, they do so in a way that does not change the flux.

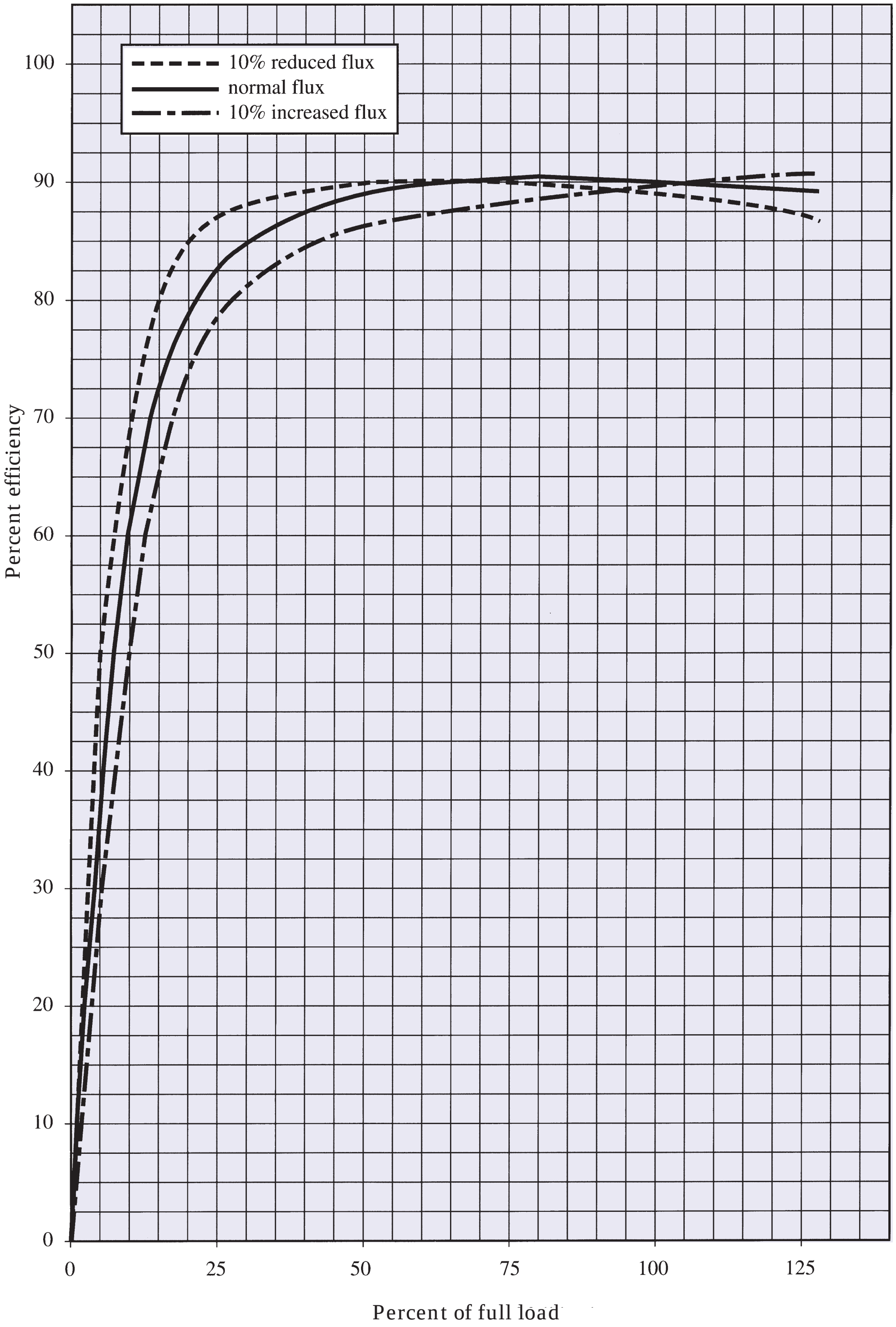


Fig. 10 Effect of flux changes on efficiency curves

APPENDIX 2

BURN-OUT OVENS AND THEIR EFFECT ON STATOR CORE LOSSES

For a considerable time, there has been evidence that uncontrolled or excessive heating of wound stators prior to stripping can cause irreversible increases in core losses (specifically, the eddy current loss component) by damaging the insulating film on the laminations. On the other hand, the stripping of the winding is made easier, the higher the temperature employed.

Believing that too little is known about this subject, the producers of this Guide decided to commission a research project, with the objective of providing test evidence of the effects on stator core loss of burn-out procedures performed over a range of temperatures, so that the results might lead to a concensus within the electric motor repair industry regarding the Best Practices for the burn-out process.

Two companies collaborated in the project: motor repairers Dowding & Mills and motor manufacturers Brook Hansen.

The Research Project

A total of 34 motors were supplied by the manufacturers and subjected to the following routine:

1. The assembled motors were quantitatively tested by the manufacturers for core losses, dismantled, and the stators sent to the repairers.
2. The stators were heated singly in a burn-out oven under controlled temperature/time cycles, the windings stripped, the stators cleaned and returned to the manufacturers.
3. The stators were rewound to the original specifications, re-assembled with the original parts, and re-tested for core losses.

The burn-out temperatures to which the stators were exposed ranged from 300 to 400° C in 20° C increments, plus 450 and 500° C, all with a heating time of 5 hours. Throughout the programme, periodic checks by contact probes showed close correlation between the maximum core temperatures and the control settings on the oven.

The Test Motors

All the motors were 4 pole 5.5 kW in frame D132S, but were of three different types.

13 were the old design standard motors, of aluminium alloy construction.

13 were the old design “Energy Efficient” motors, of cast-iron construction. (These designs have been manufactured for more than a decade, but are now being phased out of production.)

8 were pre-production samples of the new “Higher Efficiency” motors, of aluminium alloy construction, which are now the standard range.

In-so-far as the research project is concerned, the significant differences between the three motor types are the laminations. All of them used semi-processed steel, the full properties of which are developed after punching, by annealing in an oxygen-free de-carburising atmosphere, followed by cooling off in an oxidising atmosphere to form the blue/black oxide insulating film. However, the differences were as follows:

Old design standard motors used 0.65mm “Newcor”: low-carbon silicon-free steel.

Old design "Energy Efficient" used 0.65mm "Losil": low-carbon low-silicon steel. (In both these old designs, the inter-lamination resistance consisted solely of the oxide film.)

The new "Higher Efficiency" used a new grade steel whose details are not yet published, but which is known to be coated with a micro-film of an inorganic based varnish known as L3, which withstands annealing temperatures, and permits penetration of the furnace atmospheres which decarburise and oxide-coat the laminations. This heat-resistant varnish film significantly increases the ability of these new motors to survive the burn-out process, without detriment to the core losses, as shown by the following results.

The Results

The results of the tests on the motors with oxide coated laminations are depicted graphically in Figs. 11 and 12. The core losses were virtually unaffected at temperatures up to 360° C, but progressively increased at higher temperatures.

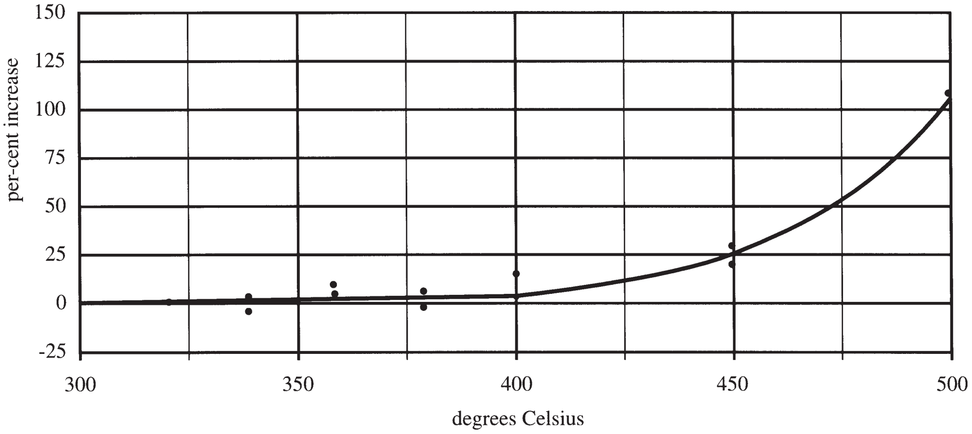


Fig. 11 Effect of burn-out temperature on core losses: old design standard motors.

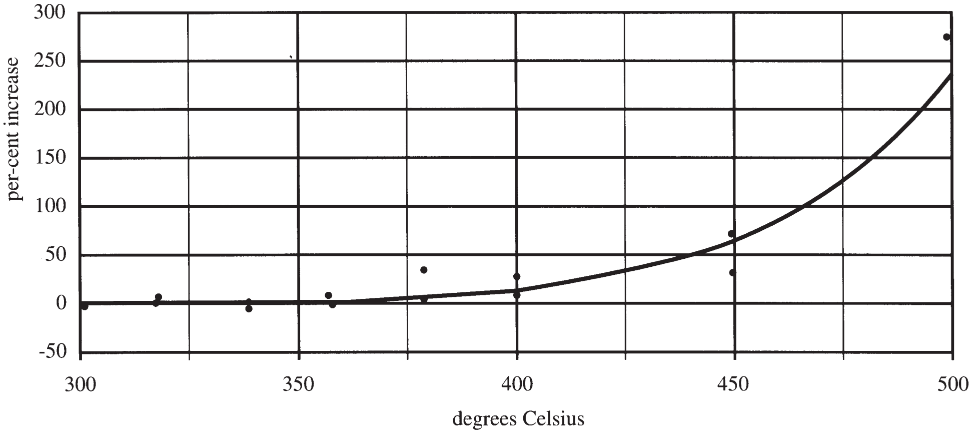


Fig. 12 Effect of burn-out temperature on core losses: old design "Energy Efficient" motors.

However, Fig. 13 shows that the new design motors, incorporating the L3 varnish-coated laminations showed no deterioration in core loss, regardless of burn-out oven temperature.

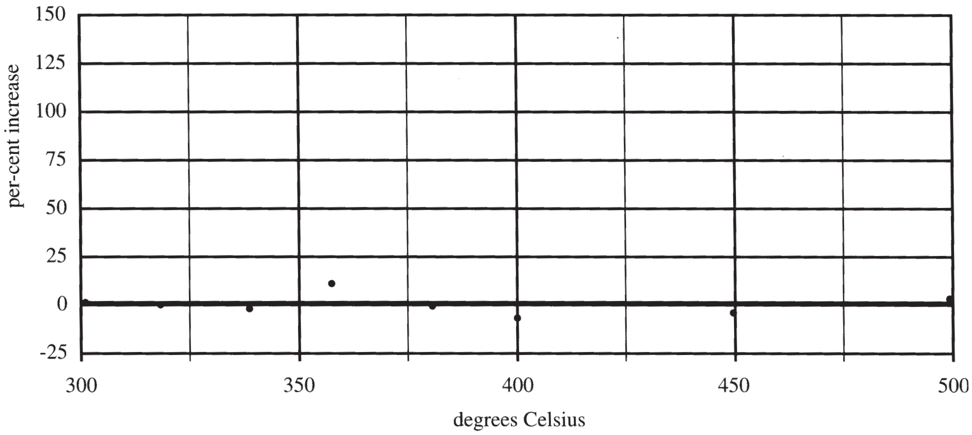


Fig.13 Effect of burn-out temperature on core losses: new “Higher Efficiency” motors.

Because the project at that stage had been restricted to motors of only one make and size, and without investigating the effect of repeated repairs, it was decided to take account of these limitations by extending the programme, as follows:

Extension of the Project

Six additional motors, all having conventional oxide-coated laminations, were subjected to the same routine as before, with the burn-outs controlled at 360° C.

Effect of Successive Rewinds

Two of the old design D132S motors were subjected to 2 successive burn-outs, and to typify repair shop practice, epoxy trickle impregnation was employed. One motor experienced 13% increased core losses after the additional burn-out; the other showed zero increase.

Different Source of Manufacture

Two motors were selected of the same size and rating as for all the previous tests, but sourced from an importer of well-known motors manufactured in mainland Europe. No significant changes in the core losses occurred.

Different Motor Size

Two 22 kW D180L test motors supplied by Brook Hansen showed no significant changes in core losses after burn-out.

Conclusions

- *Stators up to and including size D180L (22 kW) will not experience increased core losses after 5 hours burn-out at a controlled temperature of 360° C maximum. (Experience has shown that effective burn-out is achievable at this temperature, the required process time being dependant on stator size, but generally under 5 hours.)*
- *Uncontrolled or excessive burn-out temperatures are likely to degrade those stator cores which rely solely on the oxide film to insulate the laminations. The extent to which the core losses increase depends on the excess temperature.*
- *Excessive burn-out temperatures do not affect the core losses of stators incorporating core steels pre-coated with L3 or equivalent heat resistant varnish, but may cause mechanical distortion of stator frames.*
- *Previously rewound stators could be more vulnerable to second or subsequent burn-outs.*

- *Motors larger than frame size 180 were not included in the research project. It is therefore not known whether burn-out at 360°C is satisfactory for all oxide-insulated stator cores, regardless of size. Further trials are under consideration by the AEMT covering larger sizes. In the meantime, caution is advisable when stripping larger stators, by burning out at the minimum practicable temperature. This of course does not apply to motors built from core steel with the heat-resistant varnish coating.*

APPENDIX 3

CALCULATION OF LOSSES AND EFFICIENCY FROM TEST DATA

This Appendix describes the tests and calculation sequence used in the Summation of Losses method of determining the losses and efficiency of induction motors, and compliments the final paragraphs of the section entitled “Testing the Assembled Motor.” The calculations are formulated so that they can be programmed on a computer.

It will be noted that the sequence of static, no-load and on-load tests is carried out with the motor at ambient temperature, and the I^2R losses “corrected,” where appropriate, to a standardised reference temperature.

Tests

Stator Resistance at the Ambient Temperature (and I^2R calculations). The ambient temperature θ_a in the vicinity of the motor is measured, and the d.c. resistance R_{ta} is measured between any pair of the stator’s line terminals. (If the winding phases are separately terminated, they should first be linked in the “run” connection; i.e., star or delta as appropriate.)

I^2R Calculations

In calculating the total stator I^2R at the ambient temperature, a convenient method is to use the value of the line current I in conjunction with the resistance value R_{ta} as follows:

Total stator $I^2R = 1.5\ I^2R_{ta}$

Correcting I^2R Values to the Reference Temperature of 75° C[1]

It is easily shown mathematically that this formula gives the total winding I^2R, regardless of whether the phases are connected star or delta.

I^2R losses calculated at the ambient temperature θ_a can be corrected to 75°C by applying the multiplier:

$$K_{a\text{-}75} = \frac{234.5 + 75}{234.5 + \theta_a}$$

Tests

Constant Losses (friction and windage and core losses)

The motor is run unloaded (bare shaft) at its rated voltage and frequency, and the line current Io and input watts Po are measured, after running for a short period to allow the viscosity of the lubrication in the bearings to settle down.

Calculation

Constant losses = no-load input watts reduced by the no-load I^2R

$$P_{CON} = P_o - 1.5I_o^2Rt_a$$

---

[1] The reference temperature 75° C applies to standard motors and others designed for operation within the temperature limits of Class B insulation. For special motors, designed for operation at higher temperatures, the reference becomes 115° C, in which cases this figure should replace 75 in the multiplier equation.

Test

Variable (Load-Dependant) Losses at Full Load (stator and rotor I^2R and additional load losses)

The motor is run on full load[1] at rated voltage and frequency. The current I_{FL}, watts input P_{FL} and slip s are measured.[2]

Calculation of full-load stator I^2R

Stator resistance corrected to the reference temperature, 75° C:

$$R_{t75} = R_{ta}K_{a\text{-}75}$$

F.L. stator I^2R corrected to 75° C:

$$P_{STA} = 1.5I_{FL}{}^2R_{t75}$$

Calculation of full-load rotor I^2R

F.L. rotor I^2R equals the power transmitted to the rotor multiplied by the slip.

$$= (P_{FL} - P_{CON} - 1.5I_{FL}{}^2R_{ta})s \quad \text{(at ambient temperature } \Phi_{\text{a}}\text{).}$$

$$P_{ROT} = (P_{FL} - P_{CON} - 1.5I_{FT}{}^2R_{ta})sK_{a\text{-}75} \quad \text{(corrected to 75° C)}$$

Calculation of additional load (“stray”) losses

Assumed value = 0.5% of F.L. input power

$$P_{AL} = 0.005P_{FL}$$

F.L. Motor Efficiency by Summation of Losses (corrected to 75° C reference temperature)

$$\text{Efficiency} = \frac{\text{input - summated losses}}{\text{input}} \times 100\%$$

$$= \frac{P_{EL} - (P_{CON} + P_{STA} + P_{ROT} + P_{AL})}{P_{FL}} \times 100$$

---

[1] In carrying out the full-load test, unless there is a facility for measuring the mechanical output at the shaft, the load is adjusted until the measured input power equals the *anticipated* full-load value, based on an assumed value of efficiency. If the subsequent result differs significantly from the assumed value, it becomes necessary to re-adjust the load and repeat the test.

[2] The slip can be determined by measuring the speed and the supply frequency, but preferred methods include direct measurement of the slip by stroboscopic or other means.

APPENDIX 4

GLOSSARY OF TERMS

Additional Load Losses	(More popularly known by the older term “stray losses.”) Losses other than I^2R losses which are load-dependant, and are not measured or determined during the conventional Summation of Losses tests.
Chorded	See “short-pitched.”
Coil group	A number of adjacent coils in the same phase, lying between others which are in different phases.
Coil pitch	The distance between the two sides of a coil, expressed by numbering the slots they occupy; e.g., a coil pitched 1-10 would occupy the two extremes of a slot sequence numbered 1 to 10. (See “coil span.”)
Coil span	The number of teeth spanned by a coil; e.g., a coil span of 9 is the same as a coil pitch of 1-10.
Coil sides	The two portions of a coil which lie in different slots.
Concentric winding	A winding of which each coil group comprises coils of different spans, sharing a common centre line.
Core rubs	Physical contacts between the stator bore and rotor surface, while running.
Core losses	(Sometimes known as “iron losses.”) The total losses expended in a core pack, caused by the magnetic flux reversals or variations; recognised as being the sum of two components, eddy current loss and hysteresis loss.
Double layer	(Sometimes known as “half-coil” or “half-slot.”) A lap winding having two coil sides per slot; the number of coils equals the number of slots.
Distribution factor	The factor by which the e.m.f. in a winding is reduced, owing to the phase differences between the various coils in each coil group.
E.m.f.	Electro-motive-force; voltage induced by magnetic flux.
Eddy currents	Circulating currents within the core steel, produced by cyclic flux changes; one of the causes of core losses.
Full-pitched	Describes a coil whose span equals the pole-pitch; e.g., a 4 pole 36 slot winding has a pole-pitch of 9; a full-pitched coil would also have a span of 9, equivalent to a coil pitch of 1-10.
Hysteresis loss	The power loss expended in forcing the magnetic flux in the core steel to reverse its direction twice in each cycle.
Interference fit	A fit between two concentric mating surfaces (usually cylindrical), of which the inner (prior to fitting) is larger than the outer, thus requiring force or temperature difference to engage them.
Lap winding	A winding in which one side of each coil, where it emerges from each end of its slot, lies above the nearest coil, while the opposite side lies underneath.

L.M.T.	Length of mean turn; the average length of all the turns in a winding.
“Megger”	The registered trade name of a particular instrument manufacturer, often used as a general term to describe a test measurement of electrical insulation resistance.
PAM	Pole-amplitude-modulation; (developed at Bristol University) an extension of the older principle of 2:1 ratio pole-changing with a single winding, but enabling many different pairs of speed combinations to be possible.
Pitch factor	(Sometimes called “span factor” or “chord factor.”) The factor by which the e.m.f. is reduced, owing to the phase difference beween the coil sides of a short-pitched coil.
Short-pitched	(Sometimes called “short span” or “chorded.”) Describes a coil whose span is less than the pole pitch; e.g., further to the example given to illustrate “full-pitched,” a short-pitched coil in a 4 pole 36 slot winding would be pitched 1-9 or less.
Single-layer	A winding having one coil side per slot; the number of coils equals half the number of slots; (the term is usually applied to lap windings, in which case alternative descriptions would be “whole-coil” and “basket”).
“Stray” losses	See “additional load losses.”
Summation of Losses	A method of testing and declairing the efficiency of an electric motor, whereby instead of measuring mechanical power, the total of the component losses is determined and subtracted from the electrical input.
Three-tier	A type of concentric winding, in which the three phases are separately inserted in sequence; there is usually one coil group per pole per phase; e.g., 12 groups in a 4 pole winding.
Two-tier	A type of concentric winding, in which half of the coils comprising alternate coil groups are inserted first, followed by the insertion of the remainder; there is usually one coil group per pair of poles per phase; e.g., 6 groups in a 4 pole winding.

APPENDIX 5

CHECKLIST OF BEST PRACTICES TO MAINTAIN ENERGY EFFICIENCY

		Page
Preliminary Inspection	✓ To identify damage and assess whether the condition of the stator core and/or the rotor may result in increased losses. ✓ To assess whether the stator has been rewound previously, employing procedures which may not have complied with Good Practice as herein defined. ✓ To advise customer of such assessments and discuss the course of action.	**7**
Repair or Replacement of Parts	✓ To make decisions, based on whether the repair option will achieve the objective of the Guide. ✓ Any machining operations should aim to ensure correct, uniform air-gap and correct fits of spigots, bearings and seals, and of the stator core in its frame. ✓ Any replacements to be identical ex-factory parts. ✓ Proprietary fans, if used, to match closely the original.	**9**
Rotor Repairs	✓ To avoid damage to a shrink-fitted rotor when removing a damaged shaft. ✓ To check (and if necessary correct) eccentricity of the rotor surface. ✓ To substitute an identical relacement for a damaged die-cast rotor. ✓ To ensure sound joints when repairing fabricated cage rotors. ✓ To ensure correct replacement of bars, rings and laminations. ✓ To avoid excessive skew of any rebuilt or replaced rotor.	**11**
Recording Winding Details	✓ To assess whether the winding is original. ✓ To measure and record the existing winding accurately, including configuration, conductor size, turns per coil, connections and end-winding dimensions. ✓ If in doubt regarding originality, consult manufacturer or check in-house records of similar motors. ✓ To use or establish a database of standard motor windings.	**13**
Stripping the Stator Winding	✓ To avoid mechanical damage to the core during stripping. ✓ To avoid thermal damage to the core, by the following safeguards: ● Temperature control within strict upper limits, during any burn-out operation. ● Periodic monitoring and calibration of temperature controls.	**14**
Specifying the Replacement Winding	✓ To exactly copy the original; **alternatively:** ✓ To substitute a winding configuration of equal or better energy efficiency, observing the recommendations in this Guide. **In particular:** ● To compensate, if appropriate, a change in coil pitch. ● To ensure the winding resistance does not increase.	**17**

		Page
Cleaning and Inspecting the Stripped Stator Core	✓ To avoid damage by thermal or mechanical methods of cleaning the core. ✓ To use minimum force when repairing minor mechanical damage to the end laminations. ✓ To use a core tester, if core pack quality is suspect.	**21**
Rewinding	✓ To select a coil former which minimises the LMT and keeps end-winding dimensions within the original.	**22**
Testing the Wound Stator	✓ To check each phase resistance and compare with any available data from identical motors. ✓ To surge test for phase balance.	**23**
Cleaning the Wound Stator	✓ To ensure freedom from varnish deposits in the stator bore and on spigots and machined faces.	**24**
Re-assembly	✓ To ensure freedom from foreign bodies in the air-gap. ✓ To clean spigots and mating faces, thus minimising air-gap eccentricity and bearing misallignment. ✓ To avoid distortion caused by excessive force during assembly. ✓ To compensate for rotor eccentricity by machining. ✓ Routinely to replace bearings and seals. ✓ To shrink-fit replacement bearings, and to maintain alignment and correct axial clearance.	**25**
Testing After Assembly	✓ To include measurement of no-load watts in the routine test schedule. ✓ To consider setting up a load-test facility.	**28**

NOTES

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